A 2.3-GHz Cryogenically Cooled HEMT Amplifier for DSS 13

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A prototype 2.3-GHz (S-band) high electron mobility transistor (HEMT) amplifier/ closed-cycle refrigerator (CCR) system was installed in the DSS-13 feedcone in August 1986, replacing the 2.3-GHz maser. The amplifier is cryogenically cooled to a physical temperature of 12 K and provides 31.5 K antenna system noise temperature and 29 dB of gain. The HEMT device used in the amplifier is a prototype developed for JPL under an R&D contract with the General Electric Company.

I. Introduction

Masers are the lowest noise amplifiers known. They have been used in the Deep Space Network for over 25 years for spacecraft downlink communication and navigation. Their 4.5-K cooling requirements and their complexity make them costly to implement and to maintain. Cryogenically cooled high electron mobility transistor (HEMT) amplifiers [1] are approaching the noise performance of the maser in the 1- to 4-GHz region at one-fifth the cost. This report describes the design, assembly, and performance of the first HEMT/CCR system designed for the DSN. It operates over an instantaneous bandwidth of 2220 to 2330 MHz (limited by an input bandpass filter) with a nominal input noise temperature of 8.7 K at the room temperature waveguide input flange (Table 1). Antenna system noise temperature at 2295 MHz was 31.5 K in comparison to the maser system noise temperature of 28.7 K (Table 2). This higher system noise temperature is offset by significant cost savings, greater reliability, and a wider bandwidth capability useful for VLBI experiments.

II. General Description

Figure 1 shows a block diagram of the DSS-13 2.3-GHz microwave front end, including the 2.3-GHz HEMT/CCR system. Figure 2 shows a photograph of the HEMT/CCR package with vacuum housing and radiation shield removed to show the components mounted on the 12-K refrigerator station. The 12-K closed-cycle refrigerator contains a cryogenically cooled input transmission line, a cryogenic bandpass filter, a cryogenic isolator, and a three-stage amplifier which contains a HEMT in the first stage and GaAs FET devices in the second and third stages.

III. Detailed Description

A. Cryogenic Input Transmission Line

The function of the input transmission line is to transmit the input RF signal from the room temperature WR 430 waveguide flange to the cryogenic low-noise amplifier while adding the least noise possible, adding an acceptable amount of heat load to the CCR, and remaining within the size constraints of the refrigerator. The input signal is converted from waveguide to a coaxial line with a copper center conductor that is cooled along its entire length to a temperature of 12 K and with an outer conductor (0.5-inch OD, 0.010-inch-wall stainless steel) that varies in temperature from 300 K (room temperature) to 12 K along its length. A quartz dome vacuum window is epoxied into the WR 430 waveguide/coaxial transition so that the entire coaxial center conductor (including probe section in the WR 430 waveguide) and outer conductor are in a thermally insulating vacuum environment. This assembly has been used previously in Block IV and Block V traveling-wave masers and is described in [2]. The noise contribution of this assembly is estimated to be less than 0.5 K.

B. Cryogenic Bandpass Filter

HEMT and FET amplifiers are inherently very broadband devices. The amplifier in this system has over 10-dB gain from 1.0 to 3.4 GHz. Therefore, it was deemed necessary to include a bandpass filter to protect the system from out-of-band radio frequency interference (RFI) and from transmitter leakage when operating in a diplexed mode on the antenna. The filter is an evanescent mode, six-section unit supplied by K&L Microwave. This particular design was selected among other designs for the following reasons: (1) its small size permitted convenient mounting on the 12-K stage of the refrigerator; (2) the frequency shift from room temperature to 12 K is minimal (7.5 MHz); and (3) attenuation at the transmitter frequency (2120 MHz) is –55 dB. The filter is made of aluminum and is silver-plated to give the lowest microwave surface resistivity at 12 K. The noise contribution of this assembly is calculated to be approximately 0.9 K.

C. Cryogenic Isolator

A cryogenically cooled isolator is included at the input of the HEMT amplifier to provide good input match over the entire bandwidth. The cryogenic isolator, supplied by Passive Microwave Technologies, has a return loss of greater than 15 dB at 2200 to 2330 MHz and an insertion loss of 0.3 dB. The estimated noise contribution of this assembly is approximately 1.5 K.

D. Interconnecting Coaxial Lines

The three coaxial lines, which interconnect the cryogenic input transmission line, cryogenic bandpass filter, cryogenic isolator, and HEMT amplifier input, are all 4-inch lengths of 0.141-inch semi-rigid copper coaxial cable. The total estimated noise contribution of these lines is 1.2 K, including connector losses and mismatch loss.

E. HEMT Amplifier Module

The three-stage HEMT/FET/FET amplifier module is shown in Fig. 3, and the schematic diagram of the unit is shown in Fig. 4. The input network, which can transform a 50-ohm source (Z0) to the desired source impedance, consists of a movable quarter-wave transmission line with a characteristic impedance of 35 ohms in cascade with an adjustable length of transmission line that has a characteristic impedance of 50 ohms. The real part of the source impedance is varied by changing the diameter and/or the surrounding dielectric of the sliding quarter-wave slug; the distance, L, between this slug and the HEMT device determines the reactance (and hence the resonant frequency) of the input network. A center conductor (0.072-inch diameter) in a square outer conductor (0.157-inch width), as suggested by Tomassetti [3], provides the 50-ohm transmission line (Z0). For the case of this particular amplifier, the quarter-wave sliding transformer (T1) is simply a rectangular Teflon slug that fills the coaxial line and is 0.915 inch in length. It has a 0.073-inch-diameter center hole which slides over the center conductor of the transmission line. Following the coaxial input matching circuit is a three-stage microstrip circuit board modified from a Berkshire Technologies commercial design.

The first-stage HEMT (Q1) is a 1/4-micrometer device supplied by General Electric. The second-stage MGF 1412 (Q2) and third-stage MGF 1402 (Q3) FET devices are supplied by Mitsubishi Electric. The source inductance feedback provided by L3 causes the optimum input VSWR of the module to coincide with minimum noise temperature. However, the bandwidth of the resulting input impedance match is narrow (approximately 100 MHz). A cryogenic isolator was included to improve input VSWR further and to ensure stability in the antenna environment. The source inductance feedback technique was suggested by Nevin and Wong [4] and was described for a cryogenically cooled GaAs FET amplifier by Williams, Lum, and Weinreb [5]. All inductors are made with 0.008-inch-diameter phosphor-bronze wire except for L3, which is made by the use of the source tab of the packaged HEMT together with a small grounding strap. Ferrite beads are used on the Q1 drain tab and on the Q2 gate and drain tabs to help quench parasitic oscillations at high gigahertz frequencies.

Zener diodes CR1 through CR6 (1N5232B) are employed on the gates and drains of the HEMT and FETs to protect them from overvoltage. An output 10-dB chip attenuator P1 is used to ensure >20 dB output return loss. Low-temperature HEMT performance is somewhat complicated by the formation of deep electron traps, which leads to "collapse" of the drain current–voltage characteristics at cryogenic temperatures [6]. This problem is alleviated by illuminating the HEMT junction with a low level of light. An LED mounted in the cover of the amplifier provides this function. The noise contribution (at 2295 MHz) of the completed three-stage amplifier is 4.6 K with 29 dB of gain (which includes the 10-dB output attenuator). The noise temperature of the amplifier module (see Fig. 5) was measured by using a Hewlett-Packard

HP 346B calibrated noise source connected to the amplifier input through a cooled 20-dB Narda Model 4779 attenuator.[1]

F. Closed-Cycle Refrigerator

The Model 350 Cryodyne refrigerator and compressor is supplied by Cryogenics Technology, Inc. (CTI). The refrigerator is enclosed in a vacuum housing and radiation shield designed specifically for DSN applications. The first stage of the refrigerator operates at 50 K and the second stage at 12 K. The refrigerator is designed to provide 15 watts of cooling capacity at 70 K and 3 watts of cooling capacity at 15 K. Cool-down time of the HEMT/CCR system is approximately 3 hours.

IV. DSS-13 Installation

The measured input noise temperature of the assembled HEMT/CCR package was 7.4 to 9.5 K across the 2200- to 2300-MHz range, as shown in Fig. 5. On August 19, 1986, the HEMT/CCR was first installed without the cryogenic bandpass filter. System noise temperature was measured with the antenna at zenith during clear weather. On August 22, 1986, the cryogenic bandpass filter was installed in the HEMT/CCR system, and the system noise temperature was again measured. The results of these measurements are shown in Fig. 6.

Since the time of installation, there have been no electronics failures. One drive unit failure occurred, which was attributed to oil carryover from a faulty compressor. The system has been in nearly continuous operation up to the time of this writing.

[1] S. Weinreb and R. Harris, *Low Noise, 15 GHz, Cooled, GaAs FET Amplifier*, NRAO Internal Report No. 235, National Radio Astronomy Observatory, Charlottesville, Virginia, September 1983.

V. Conclusions

The 2.3-GHz HEMT/CCR system has proven, as expected, to be a more reliable system than the maser/CCR system. The noise temperature of future HEMT devices is expected to improve, and it is clear that the noise contribution of other cryogenic input components, such as the isolator and filter, can also be lowered. Therefore, the noise performance of this system can probably be made to surpass that of the DSN Block III TWM/CCR (5- to 8-K noise temperature) during the coming year.

Acknowledgments

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References

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[3] G. Tomassetti, S. Weinreb, and K. Wellington, "Low Noise 10.7 GHz Cooled GaAs FET Amplifier," *Electronics Letter*, vol. 17, no. 25/26, pp. 949–951, December 10, 1981.

[4] L. Nevin and R. Wong, "L-Band GaAs FET Amplifier," *Microwave Journal*, vol. 22, no. 4, pp. 82–83 and 92, April 1979.

[5] D. Williams, W. Lum, and S. Weinreb, "L-Band Cryogenically Cooled GaAs FET Amplifier," *Microwave Journal*, pp. 73–76, October 1980.

[6] A. W. Swanson, "Pseudomorphic HEMT," *Microwaves and RF*, vol. 26, no. 3, pp. 139–150, March 1987.

Table 1. Noise temperature budget for 2.3-GHz HEMT/CCR system at 2295 MHz

System component	Noise contribution, K	
	With maser	With HEMT
Sky	3.5	3.5
Antenna	5.0	5.0
Horn	1.2	1.2
Combiner and yoke	10.0	10.0
54-dB coupler	0.2	0.2
Waveguide switch	0.5	0.5
Waveguide and bends	2.0	2.0
Waveguide bandpass filter	3.4	–
Dual cross guide coupler	0.4	0.4
Low noise amplifier	2.5	8.7
Total system noise temperature	28.7	31.5

Table 2. Estimated noise contributions to DSS-13 system noise temperature at 2295 MHz using maser/CCR and HEMT/CCR

System component	Noise contribution, K
Input line	0.3
Filter	0.9
Isolator	1.5
Coax	1.2
HEMT amplifier module	4.6
Follow-up amplifier	0.2
Total input noise temperature	8.7

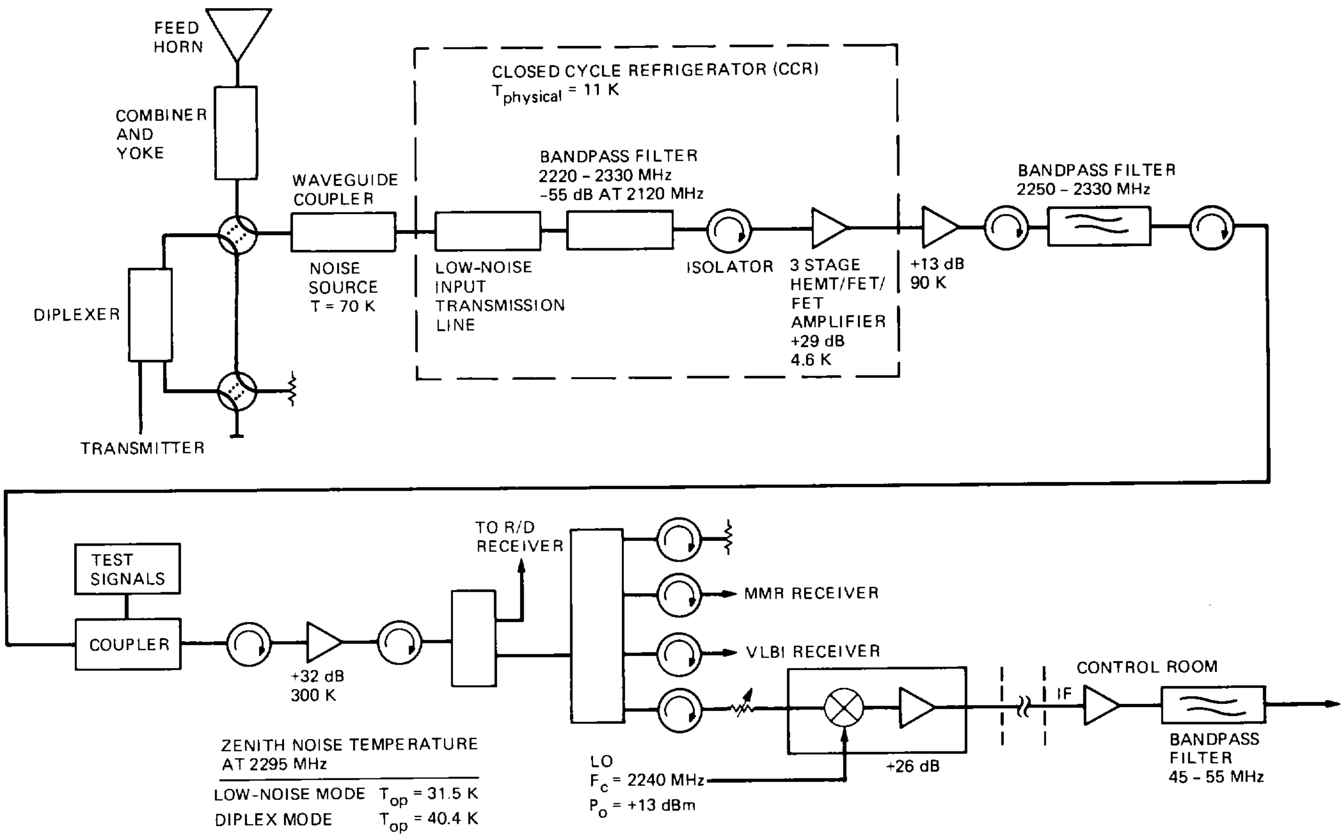

Fig. 1. DSS-13 S-band receiver system block diagram

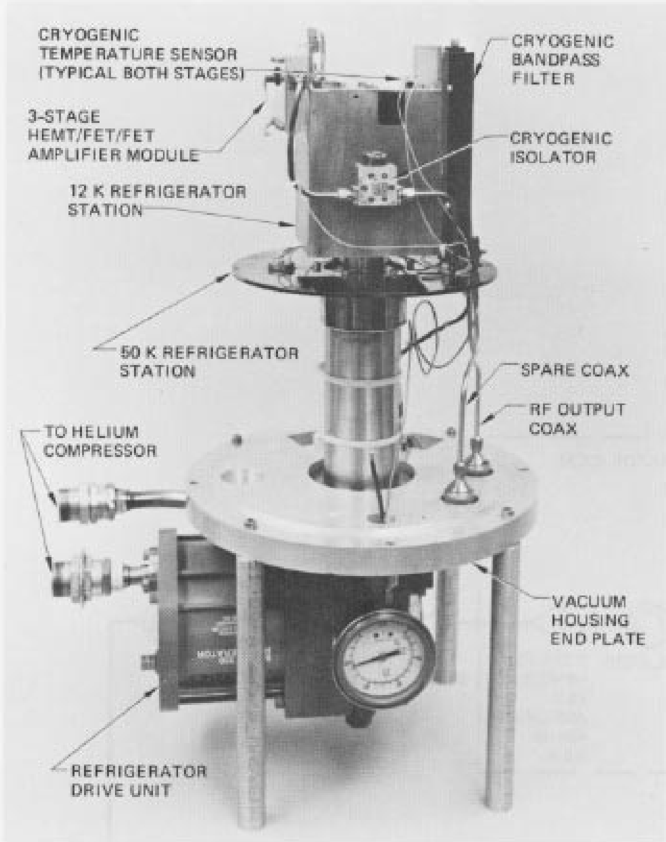

Fig. 2. HEMT/CCR package

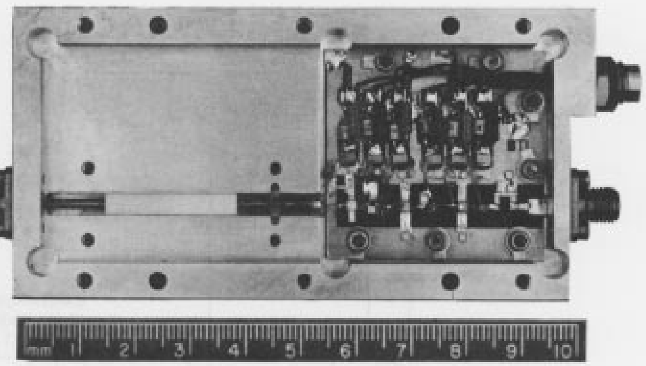

Fig. 3. HEMT/FET/FET amplifier module

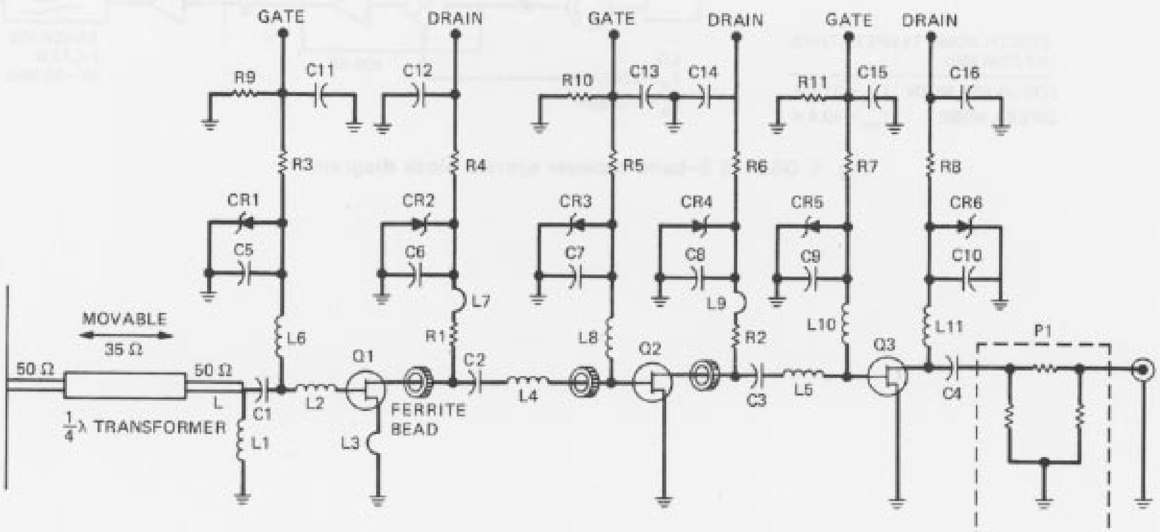

Fig. 4. Three-stage amplifier schematic diagram

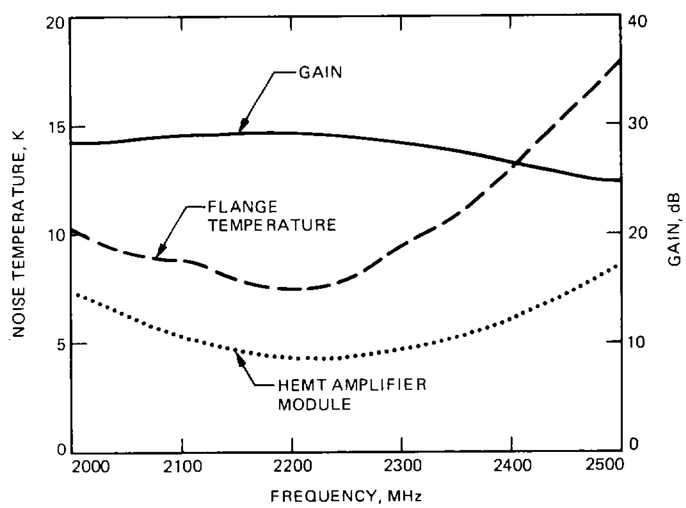

Fig. 5. Noise temperature of HEMT amplifier module and noise temperature (and gain) reference at the WR 430 waveguide flange with cryogenic filter not installed

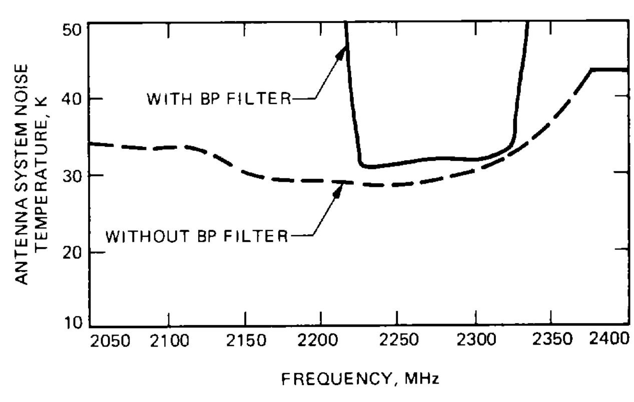

Fig. 6. DSS-13 antenna system noise temperature with and without the cryogenic bandpass filter